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DERIVATION OF RECURSIVE UPDATE EQUATIONS FOR JOINT REPRESENTATION MIXTURE MODELS

BY GEORGE W. ROGERS AND RICHARD A. LOREY
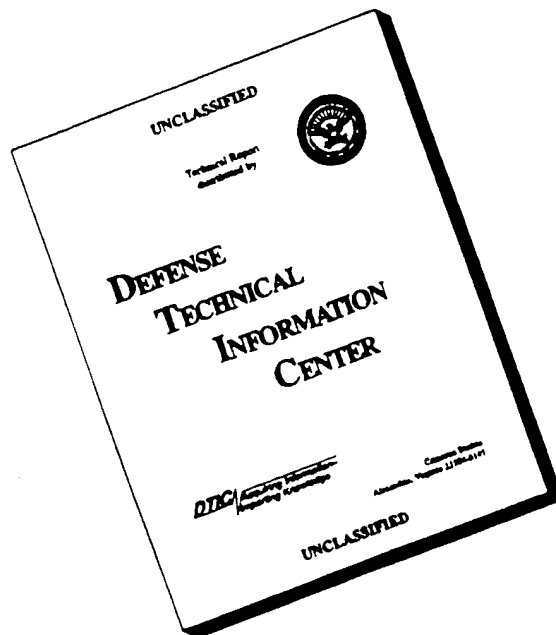SYSTEMS RESEARCH AND TECHNOLOGY DEPARTMENT

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The joint representation mixture model is defined, likelihood functions corresponding to different levels of data categorization with respect to class are presented along with the iterative expectation-maximization (E-M) equations, and the resultant recursive E-M equations are derived.

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FOREWORD

Density estimation plays a central role in probabilistic pattern recognition and signal processing. As data sets get larger, the cost of identifying a definitive class with each observation can become prohibitive. Instead, it becomes important to develop ways to process the data in ways that make use of all available information.

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INTRODUCTION

Finite mixture models have proven to be quite flexible as parametric probability density function estimators.[1,2] Recently an adaptive mixture model was presented whose complexity or number of terms is determined in a data driven manner.[3] This approach has made possible the use of mixture models within a semiparametric setting, and thus of much more general applicability/ utility than was possible under rigid parametric assumptions.

This semiparametric use of mixture models has resulted in efforts to develop alternative adaptive mixture model algorithms.[4,5] Recent applications of semiparametric mixture model density estimation can be found in References 6 through 11. Thus, in addition to the traditional parametric uses of mixture models, the semiparametric application of mixture models is now well established.

One of the problems that arises in many applications of mixture models to density estimation of large scale data sets is that, as the size of the data set increases, the class labeled data becomes a (small) subset of the total data set; that is, while many small data sets may have all the observations labeled as to class membership, large data sets often consist of labeled subsets plus a potentially large unlabeled subset.

The reason for this can be illustrated with an image processing example. Suppose that features are to be computed for each pixel for a number of images and that densities are to be computed for each class. Depending on the problem, the classes may correspond to vehicles, buildings, woods, and open terrain, or to tumorous and nontumorous tissue. If all the available data is to be used, the work in allocating each original pixel to one of the classes can easily become prohibitive. The more usual case is that only a representative subset of training data are class labeled with the balance either uncategorized or partially categorized. An example of the latter case is that it may be easy to say that there are no vehicles in this image, no buildings in that one, and so on but very difficult or time consuming to identify each pixel corresponding to each class in each image. It is often the case in medical imagery that ground truth cannot be established definitively without a biopsy, again leading to less than full categorization of the observations.

Thus it is desirable to have a unified framework for handling this combined supervised (class labeled data)/unsupervised (unlabeled data) problem. This was the motivation behind the development of joint representation mixture models.[12] When dealing with large data sets, by which we mean 100,000 observations or more, the iterative expectation-maximization (E-M) equations often become impractical. One method of dealing with this much data is to go to recursive formulations of the E-M equations. This approach also makes possible the implementation of the adaptive mixure model approach.[3] The derivation of the recursive E-M equations for joint representation mixture models is the focus of this report.

JOINT REPRESENTATION MIXTURE MODELS

FINITE MIXTURE MODELS

Given a probability density function that can be represented as a finite (g term) mixture model

$$p(x|\psi) = \sum_{i=1}^{g} \pi_i f(x;\theta_i), \tag{1}$$

where $f(\bullet|\theta)$ denotes a generic member of the chosen parametric family, the likelihood function for n observations is given by

$$L(\psi) = \prod_{j=1}^{n} \sum_{i=1}^{g} \pi_i f(x_j;\theta_i). \tag{2}$$

The vector θ_i represents the parameter set for the ith mixture component while ψ represents the combined total parameter set including the mixing coefficients π_i. The log-likelihood function is

$$lnL(\psi) = \sum_{j=1}^{n} ln\left[\sum_{i=1}^{g} \pi_i f(x_j;\theta_i)\right]. \tag{3}$$

The maximum likelihood update equations can be obtained by taking derivatives of the log-likelihood function with respect to the mixture model parameters, setting the resulting expressions equal to zero, and solving for the parameters.

JOINT REPRESENTATION MIXTURE MODELS

Consider the Joint Representation Mixture Model defined by

$$p(x|\psi) = \sum_{i=1}^{g} p(\text{term } i) p(x|\text{term } i) \sum_{m=1}^{M} p(\text{class } m|\text{term } i) = \sum_{i=1}^{g} \pi_i f(x;\theta_i) \sum_{m=1}^{M} \zeta_{im} \tag{4}$$

where $\zeta_{im} = p(\text{class } m|\text{term } i)$ is an intra-term class mixing coefficient that gives the relative proportion of the ith term associated with the mth class with the constraint

$$\sum_{m=1}^{M} \zeta_{im} = \sum_{m=1}^{M} p(\text{class } m|\text{term } i) = 1. \tag{5}$$

This constraint merely says that for each term independently, the class mixing coefficients must sum to one, or equivalently, that an observation from term i must belong to one of the M classes with probability one.

The mixture model defined in Equations (4) and (5) represents a significant departure from traditional mixture model usage. Historically a single mixture model has been used for either performing unsupervised clustering or to generate a probability density function for observations from a single class. If observations from multiple classes are to be dealt with, then a separate mixture model is developed for data from each class. This latter approach leaves open the question of how to incorporate partially (class) categorized or uncategorized observations when there are separate mixture models for each class. As will be seen, the joint representation formulation leads to a unified treatment of these cases.

JOINT REPRESENTATION MIXTURE MODEL LIKELIHOOD FUNCTIONS

The likelihood function for class categorized data is

$$
\begin{aligned}
L_c(\psi) &= \prod_{j=1}^{n_c} \prod_{m=1}^{M} \left\{ \left[p\left(x_j \,\middle|\, (\psi \cap \text{Class } m)\right) \right]^{z_{jm}} \right\} \\
&= \prod_{j=1}^{n_c} \prod_{m=1}^{M} \left\{ \left[\sum_{i=1}^{g} \zeta_{im} \pi_i f(x_j;\theta_i) \right]^{z_{jm}} \right\}.
\end{aligned}
\tag{6}
$$

Here, z_{jm} is a binary valued class indicator function. For observation j from class h, $z_{jh} = 1$ and $z_{jm} = 0$ for $m \neq h$. It thus can be considered as a picking function. It is used to *pick out* the desired contribution to the likelihood function. For each term in the product where it has the value zero, the contribution to the product is one so that the likelihood is unaffected. The log-likelihood function for class categorized data can be written

$$
\begin{aligned}
lnL_c(\psi) &= \sum_{j=1}^{n_c} \sum_{m=1}^{M} ln\left\{ \left[\sum_{i=1}^{g} \zeta_{im} \pi_i f(x_j;\theta_i) \right]^{z_{jm}} \right\} \\
&= \sum_{j=1}^{n_c} \sum_{m=1}^{M} z_{jm} ln\left\{ \sum_{i=1}^{g} \zeta_{im} \pi_i f(x_j;\theta_i) \right\} \\
&= \sum_{j=1}^{n_c} ln \sum_{i=1}^{g} \sum_{m=1}^{M} z_{jm} \zeta_{im} \left[\pi_i f(x_j;\theta_i) \right].
\end{aligned}
\tag{7}
$$

To write down the likelihood for partially (class) categorized data, first consider the likelihood appropriate for the case where the data is both class and term categorized. In this case, the

likelihood is

$$L_{ct}(\psi) = \prod_{j=1}^{n_c} \prod_{m=1}^{M} \prod_{i=1}^{g} \left\{ \left[\zeta_{im} \pi_i f(x_j; \theta_i) \right]^{z_{jm} z_{ji}} \right\}. \tag{8}$$

Where as before, z_{jm} (z_{ji}) is a binary valued class (term) indicator function. For observation j from class h, $z_{jh} = 1$ and $z_{jm} = 0$ for $m \neq h$, while for observation j from term k, $z_{jk} = 1$ and $z_{ji} = 0$ for $i \neq k$.

In the absence of complete knowledge of z_{jm} and/or z_{ji} the usual procedure is to use expected values for either/both as

$$E(z_{jm}) = \xi_{jm} \tag{9}$$

and

$$E(z_{ji}) = \tau_{ij}^p. \tag{10}$$

Then for partially (class) categorized data, the likelihood is

$$L_p(\psi) = \prod_{j=1}^{n_p} \prod_{i=1}^{g} \prod_{m=1}^{M} \left\{ \left[\zeta_{im} \pi_i f(x_j; \theta_i) \right]^{\xi_{jm} \tau_{ij}^p} \right\} \tag{11}$$

whence

$$
\begin{aligned}
lnL_p(\psi) &= \sum_{j=1}^{n_p} \sum_{i=1}^{g} \sum_{m=1}^{M} \left\{ \xi_{jm} \tau_{ij}^p ln \left[\zeta_{im} \pi_i f(x_j; \theta_i) \right] \right\} \\
&= \sum_{j=1}^{n_p} \sum_{i=1}^{g} \sum_{m=1}^{M} ln \left\{ \left[\zeta_{im} \pi_i f(x_j; \theta_i) \right]^{\xi_{jm} \tau_{ij}^p} \right\}
\end{aligned}
\tag{12}
$$

where ξ_{jm} is a prior or expected probability of class membership with

$$\sum_{m=1}^{M} [\xi_{jm}] = 1, \tag{13}$$

and

$$\tau_{ij}^p = \frac{\pi_i f(x_j; \theta_i)}{\displaystyle\sum_{i=1}^{g} \pi_i f(x_j; \theta_i)} \tag{14}$$

is the expectation (posterior probability) that the jth observation came from the ith mixture term.

Since this is an expectation, it will be held fixed while taking derivatives. Two common methods for specifying partial categorization are (1) to give prior probabilities for each class for observation j, or (2) to specify that the priors are zero for some subset of the classes and to use posterior probabilities across the remaining possible classes for the *unknown* ξ_{jm}.

For uncategorized data,

$$L_u(\psi) = \prod_{j=1}^{n_u} \left[\sum_{i=1}^{g} \sum_{m=1}^{M} \zeta_{im} \pi_i f(x_j;\theta_i) \right] = \prod_{j=1}^{n_u} \sum_{i=1}^{g} [\pi_i f(x_j;\theta_i)] , \qquad (15)$$

$$lnL_u(\psi) = \sum_{j=1}^{n_u} ln \sum_{i=1}^{g} \sum_{m=1}^{M} \zeta_{im} \pi_i f(x_j;\theta_i) = \sum_{j=1}^{n_u} ln \sum_{i=1}^{g} [\pi_i f(x_j;\theta_i)] . \qquad (16)$$

For combined categorized/partially categorized/uncategorized data,

$$lnL(\psi) = lnL_c(\psi) + lnL_p(\psi) + lnL_u(\psi) \qquad (17)$$

or

$$lnL(\psi) = \sum_{j=1}^{n_c} ln \sum_{i=1}^{g} \sum_{m=1}^{M} z_{jm} \zeta_{im} [\pi_i f(x_j;\theta_i)]$$

$$+ \sum_{j=1}^{n_p} \sum_{m=1}^{M} \sum_{i=1}^{g} \xi_{jm} \tau_{ij} ln [\zeta_{im} \pi_i f(x_j;\theta_i)] + \sum_{j=1}^{n_u} ln \sum_{i=1}^{g} \pi_i f(x_j;\theta_i) . \qquad (18)$$

Historically with mixture models, reference to categorization of data has been with respect to which term of the mixture model the observation is associated. While this is logical when each term is ascribed a *class* status as in clustering, in this work, a completely different definition of categorized data is being used. In this case, the concern is that of categorizing data only with respect to class membership rather than with respect to individual mixture model terms.

To derive the maximum likelihood update equations, the parameter values that give a maximum of the log-likelihood function must be found. This can be accomplished by taking the derivative with respect to each parameter, setting it equal to zero, and solving the resultant system of equations for the parameters. This has been done previously[12] so that those results will be taken as the starting point in developing the recursive versions here.

MAXIMUM LIKELIHOOD E-M EQUATIONS

The joint representation E-M equations are[12]

$$\zeta_{im} = \left[\frac{1}{\sum\limits_{j=1}^{n_c} \sum\limits_{m=1}^{M} \tau_{ijm} + \sum\limits_{j=1}^{n_p} \tau_{ij}^{p}} \right] \left[\sum\limits_{j=1}^{n_c} \tau_{ijm} + \sum\limits_{j=1}^{n_p} \xi_{jm} \tau_{ij}^{p} \right], \qquad (19)$$

$$\pi_i = \frac{1}{(n_c + n_p + n_u)} \left[\sum\limits_{j=1}^{n_c} \tau_{ij}^{c} + \sum\limits_{j=1}^{n_p} \tau_{ij}^{p} + \sum\limits_{j=1}^{n_u} \tau_{ij}^{u} \right], \qquad (20)$$

$$\mu_i = \frac{\sum\limits_{i=1}^{n_c} \left[\tau_{ij}^{c} x_j \right] + \sum\limits_{j=1}^{n_p} \left[\tau_{ij}^{p} x_j \right] + \sum\limits_{j=1}^{n_u} \left[\tau_{ij}^{u} x_j \right]}{\left[\sum\limits_{j=1}^{n_c} \left[\tau_{ij}^{c} \right] + \sum\limits_{j=1}^{n_p} \left[\tau_{ij}^{p} \right] + \sum\limits_{j=1}^{n_u} \left[\tau_{ij}^{u} \right] \right]}, \qquad (21)$$

$$\Sigma_{ii} = \frac{\sum\limits_{j=1}^{n_c} \tau_{ij}^{c} (x_j - \mu_i)^2 + \sum\limits_{j=1}^{n_p} \tau_{ij}^{p} (x_j - \mu_i)^2 + \sum\limits_{j=1}^{n_u} \tau_{ij}^{u} (x_j - \mu_i)^2}{\left[\sum\limits_{j=1}^{n_c} \tau_{ij}^{c} + \sum\limits_{j=1}^{n_p} \tau_{ij}^{p} + \sum\limits_{j=1}^{n_u} \tau_{ij}^{u} \right]}, \qquad (22)$$

where

$$\tau_{ijm} = \frac{z_{jm} \zeta_{im} \pi_i f(x_j; \theta_i)}{\sum\limits_{i=1}^{g} \sum\limits_{m=1}^{M} z_{jm} \zeta_{im} \pi_i f(x_j; \theta_i)}, \qquad (23)$$

and

$$\tau_{ij}^{c} = \sum\limits_{m=1}^{M} \tau_{ijm} = \frac{\zeta_{im_j} \pi_i f(x_j; \theta_i)}{\sum\limits_{i=1}^{g} \zeta_{im_j} \pi_i f(x_j; \theta_i)} = \frac{\sum\limits_{m=1}^{M} z_{jm} \zeta_{im} \pi_i f(x_j; \theta_i)}{\sum\limits_{i=1}^{g} \sum\limits_{m=1}^{M} z_{jm} \zeta_{im} \pi_i f(x_j; \theta_i)}. \qquad (24)$$

Similarly

$$\tau_{ij}^p = \tau_{ij}^u = \frac{\pi_i f(x_j; \theta_i)}{\sum\limits_{i=1}^{g} \pi_i f(x_j; \theta_i)}, \tag{25}$$

where it is to be remembered that τ_{ij}^p is only computed when x_j is a partially categorized observation and similarly for τ_{ij}^u.

The E-M algorithm then consists of iterating the expectation step consisting of evaluating Equations (23), (24), and (25) for the appropriate observations and the maximization step, which consists of evaluating new parameter values using Equations (19) through (22).

The multivariate versions can be obtained by making x_j and μ_i vector quantities and Σ_i a matrix. The equations for μ_i and Σ_i become

$$\mu_i^k = \frac{\sum\limits_{i=1}^{n_c} \left[\tau_{ij}^c x_j^k \right] + \sum\limits_{j=1}^{n_p} \left[\tau_{ij}^p x_j^k \right] + \sum\limits_{j=1}^{n_u} \left[\tau_{ij}^u x_j^k \right]}{\left[\sum\limits_{j=1}^{n_c} \left[\tau_{ij}^c \right] + \sum\limits_{j=1}^{n_p} \left[\tau_{ij}^p \right] + \sum\limits_{j=1}^{n_u} \left[\tau_{ij}^u \right] \right]} \tag{26}$$

and

$$\Sigma_i^{kl} = \frac{\sum\limits_{i=1}^{n_c} \tau_{ij}^c \left(x_j^k - \mu_i^k \right) \left(x_j^l - \mu_i^l \right) + \sum\limits_{j=1}^{n_p} \tau_{ij}^p \left(x_j^k - \mu_i^k \right) \left(x_j^l - \mu_i^l \right) + \sum\limits_{j=1}^{n_u} \tau_{ij}^u \left(x_j^k - \mu_i^k \right) \left(x_j^l - \mu_i^l \right)}{\left[\sum\limits_{j=1}^{n_c} \tau_{ij}^c + \sum\limits_{j=1}^{n_p} \tau_{ij}^p + \sum\limits_{j=1}^{n_u} \tau_{ij}^u \right]}, \tag{27}$$

where the component indices are denoted by superscripts.

Finally, once the joint representation mixture model has been obtained based on any combination of class categorized, partial class categorized, and uncategorized data, if desired the probability density function for an individual class can be obtained through

$$\hat{p}\,(x|\text{Class y, }\psi) = \frac{\displaystyle\sum_{i=1}^{g} \zeta_{iy}\pi_i f(x;\theta_i)}{\displaystyle\sum_{i=1}^{g} \zeta_{iy}\pi_i} . \qquad (28)$$

This gives a properly normalized mixture model density estimate for an individual class.

These results serve as the starting point for the derivation of the recursive update equations.

DERIVATION OF RECURSIVE UPDATE EQUATIONS FOR JOINT REPRESENTATION MODEL

Recursive Update Equation for ζ

Consider first $\zeta_{im}^{(n_c+1,\,n_p)}$, which implies that the latest observation is class categorized. In terms of the E-M expression,

$$\zeta_{im}^{(n_c+1,\,n_p)} = \left[\frac{\displaystyle\sum_{j=1}^{n_c+1} \tau_{ijm} + \sum_{j=1}^{n_p} \xi_{jm}\tau_{ij}^p}{\displaystyle\sum_{j=1}^{n_c+1} \tau_{ij}^c + \sum_{j=1}^{n_p} \tau_{ij}^p} \right] \qquad (29)$$

or, equivalently

$$\zeta_{im}^{(n_c+1,\,n_p)} = \left[\frac{\{\tau_{i(n_c+1)m}\} + \displaystyle\sum_{j=1}^{n_c} \tau_{ijm} + \sum_{j=1}^{n_p} \xi_{jm}\tau_{ij}^p}{\tau_{i(n_c+1)}^c + \displaystyle\sum_{j=1}^{n_c} \tau_{ij}^c + \sum_{j=1}^{n_p} \tau_{ij}^p} \right] . \qquad (30)$$

The right-hand side of this equation can be broken into two terms, corresponding to the last observation and all previous observations, respectively.

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$$\zeta_{im}^{(n_c+1, n_p)} = \left[\frac{\tau_{i(n_c+1)m}}{\tau_{i(n_c+1)}^c + \sum_{j=1}^{n_c} \tau_{ij}^c + \sum_{j=1}^{n_p} \tau_{ij}^p} \right] + T_2 \tag{31}$$

where the second term is given by

$$T_2 = \left[\frac{\sum_{j=1}^{n_c} \tau_{ijm} + \sum_{j=1}^{n_p} \xi_{jm} \tau_{ij}^p}{\tau_{i(n_c+1)}^c + \sum_{j=1}^{n_c} \tau_{ij}^c + \sum_{j=1}^{n_p} \tau_{ij}^p} \right]. \tag{32}$$

This can be rewritten as

$$T_2 = \left[\frac{\sum_{j=1}^{n_c} \tau_{ijm} + \sum_{j=1}^{n_p} \xi_{jm} \tau_{ij}^p}{\tau_{i(n_c+1)}^c + \sum_{j=1}^{n_c} \tau_{ij}^c + \sum_{j=1}^{n_p} \tau_{ij}^p} \right] \left[\frac{\sum_{j=1}^{n_c} \tau_{ij}^c + \sum_{j=1}^{n_p} \tau_{ij}^p}{\sum_{j=1}^{n_c} \tau_{ij}^c + \sum_{j=1}^{n_p} \tau_{ij}^p} \right], \tag{33}$$

which, with a minor rearrangement of terms, becomes

$$T_2 = \left[\frac{\sum_{j=1}^{n_c} \tau_{ij}^c + \sum_{j=1}^{n_p} \tau_{ij}^p}{\tau_{i(n_c+1)}^c + \sum_{j=1}^{n_c} \tau_{ij}^c + \sum_{j=1}^{n_p} \tau_{ij}^p} \right] \left[\frac{\sum_{j=1}^{n_c} \tau_{ijm} + \sum_{j=1}^{n_p} \xi_{jm} \tau_{ij}^p}{\sum_{j=1}^{n_c} \tau_{ij}^c + \sum_{j=1}^{n_p} \tau_{ij}^p} \right]. \tag{34}$$

The last term in brackets on the right-hand side is just $\zeta_{im}^{(n_c, n_p)}$, so that

$$T_2 = \left[1 - \frac{\tau_{i(n_c+1)}^c}{\tau_{i(n_c+1)}^c + \sum_{j=1}^{n_c} \tau_{ij}^c + \sum_{j=1}^{n_p} \tau_{ij}^p} \right] \left[\zeta_{im}^{(n_c, n_p)} \right]. \tag{35}$$

Then

$$\zeta_{im}^{(n_c+1, n_p)} = \zeta_{im}^{(n_c, n_p)} + \frac{\tau_{i(n_c+1)m} - \tau_{i(n_c+1)}^c \cdot \zeta_{im}^{(n_c, n_p)}}{\tau_{i(n_c+1)}^c + \sum_{j=1} \tau_{ij}^c + \sum_{j=1} \tau_{ij}^p}.$$ (36)

Using the identity

$$\tau_{i(n_c+1)m} = z_{(n_c+1)m} \cdot \sum_{m=1}^{M} \{\tau_{i(n_c+1)m}\} = z_{(n_c+1)m} \cdot \tau_{i(n_c+1)}^c$$

the final expression can be written as

$$\zeta_{im}^{(n_c+1, n_p)} = \zeta_{im}^{(n_c, n_p)} + \frac{\tau_{i(n_c+1)}^c \cdot \left[z_{(n_c+1)m} - \zeta_{im}^{(n_c, n_p)}\right]}{\tau_{i(n_c+1)}^c + \sum_{j=1} \tau_{ij}^c + \sum_{j=1} \tau_{ij}^p}.$$ (37)

Similarly, for a partially categorized observation,

$$\zeta_{im}^{(n_c, n_p+1)} = \left[\frac{\sum_{j=1}^{n_c} \tau_{ijm} + \sum_{j=1}^{n_p+1} \xi_{jm}\tau_{ij}^p}{\sum_{j=1}^{n_c} \tau_{ij}^c + \sum_{j=1}^{n_p+1} \tau_{ij}^p}\right] = \left[\frac{\xi_{n_p+1, m}\tau_{i, n_p+1}^p + \sum_{j=1}^{n_c} \tau_{ijm} + \sum_{j=1}^{n_p} \xi_{jm}\tau_{ij}^p}{\tau_{i, n_p+1}^p + \sum_{j=1}^{n_c} \tau_{ij}^c + \sum_{j=1}^{n_p} \tau_{ij}^p}\right]$$ (38)

or, as before

$$\zeta_{im}^{(n_c, n_p+1)} = \left[\frac{\xi_{n_p+1, m}\tau_{i, n_p+1}}{\tau_{i, n_p+1}^p + \sum_{j=1}^{n_c} \tau_{ij}^c + \sum_{j=1}^{n_p} \tau_{ij}^p}\right] + T_2$$ (39)

with

$$T_2 = \left[\frac{\displaystyle\sum_{j=1}^{n_c} \tau_{ijm} + \sum_{j=1}^{n_p} \xi_{jm} \tau_{ij}^p}{\displaystyle\tau_{i,n_p+1}^p + \sum_{j=1}^{n_c} \tau_{ij}^c + \sum_{j=1}^{n_p} \tau_{ij}^p} \right] . \tag{40}$$

Proceeding as before in the completely categorized case,

$$T_2 = \left[\frac{\displaystyle\sum_{j=1}^{n_c} \tau_{ijm} + \sum_{j=1}^{n_p} \xi_{jm} \tau_{ij}^p}{\displaystyle\tau_{i,n_p+1}^p + \sum_{j=1}^{n_c} \tau_{ij}^c + \sum_{j=1}^{n_p} \tau_{ij}^p} \right] \left[\frac{\displaystyle\tau_{i,n_p+1}^p - \tau_{i,n_p+1}^p + \sum_{j=1}^{n_c} \tau_{ij}^c + \sum_{j=1}^{n_p} \tau_{ij}^p}{\displaystyle\sum_{j=1}^{n_c} \tau_{ij}^c + \sum_{j=1}^{n_p} \tau_{ij}^p} \right] \tag{41}$$

or, equivalently,

$$T_2 = \zeta_{im}^{(n_c, n_p)} \left[\frac{\displaystyle\tau_{i,n_p+1}^p - \tau_{i,n_p+1}^p + \sum_{j=1}^{n_c} \tau_{ij}^c + \sum_{j=1}^{n_p} \tau_{ij}^p}{\displaystyle\tau_{i,n_p+1}^p + \sum_{j=1}^{n_c} \tau_{ij}^c + \sum_{j=1}^{n_p} \tau_{ij}^p} \right] . \tag{42}$$

This is readily seen to be

$$T_2 = \zeta_{im}^{(n_c, n_p)} \left[1 - \frac{\displaystyle\tau_{i,n_p+1}^p}{\displaystyle\tau_{i,n_p+1}^p + \sum_{j=1}^{n_c} \tau_{ij}^c + \sum_{j=1}^{n_p} \tau_{ij}^p} \right] , \tag{43}$$

which leads to the final result for a partially categorized observation

$$\zeta_{im}^{(n_c, n_p + 1)} = \zeta_{im}^{(n_c, n_p)} + \left[\frac{\tau_{i, n_p + 1}^p}{\tau_{i, n_p + 1}^p + \sum_{j=1}^{n_c} \tau_{ij}^c + \sum_{j=1}^{n_p} \tau_{ij}^p} \right] \left[\xi_{jm} - \zeta_{im}^{(n_c, n_p)} \right] . \qquad (44)$$

Recall that no update takes place for an uncategorized observation.

Recursive Update Equation for π

Consider first $\pi_i^{(n_c + 1, n_p, n_u)}$, which implies that the latest observation is class categorized. In terms of the E-M expression,

$$\pi_i^{(n_c + 1, n_p, n_u)} = \left[\frac{\sum_{j=1}^{n_c + 1} \tau_{ij}^c + \sum_{j=1}^{n_p} \tau_{ij}^p + \sum_{j=1}^{n_u} \tau_{ij}^u}{(n_c + 1) + n_p + n_u} \right] \qquad (45)$$

or, equivalently

$$\pi_i^{(n_c + 1, n_p, n_u)} = \left[\frac{\tau_{i(n_c + 1)}^c + \sum_{j=1}^{n_c} \tau_{ij}^c + \sum_{j=1}^{n_p} \tau_{ij}^p + \sum_{j=1}^{n_u} \tau_{ij}^u}{(n_c + 1) + n_p + n_u} \right] . \qquad (46)$$

The right-hand side of this equation can be broken into two terms, corresponding to the last observation and all previous observations, respectively.

$$\pi_i^{(n_c + 1, n_p, n_u)} = \frac{\tau_{i(n_c + 1)}^c}{(n_c + 1) + n_p + n_u} + \left[\frac{\sum_{j=1}^{n_c} \tau_{ij}^c + \sum_{j=1}^{n_p} \tau_{ij}^p + \sum_{j=1}^{n_u} \tau_{ij}^u}{(n_c + 1) + n_p + n_u} \right] \qquad (47)$$

This can be rewritten as

$$\pi_i^{(n_c + 1, n_p, n_u)} = \frac{\tau_{i(n_c + 1)}^c}{(n_c + 1) + n_p + n_u} + \left[\frac{n_c + n_p + n_u}{(n_c + 1) + n_p + n_u}\right]\pi_i^{(n_c, n_p, n_u)}, \quad (48)$$

which becomes

$$\pi_i^{(n_c + 1, n_p, n_u)} = \pi_i^{(n_c, n_p, n_u)} + \frac{1}{(n_c + n_p + n_u) + 1}\left[\tau_{i(n_c + 1)}^c - \pi_i^{(n_c, n_p, n_u)}\right]. \quad (49)$$

Consider next $\pi_{im}^{(n_c, n_p + 1, n_u)}$, which implies that the latest observation is partially class categorized. In terms of the E-M expression,

$$\pi_i^{(n_c, n_p + 1, n_u)} = \left[\frac{\displaystyle\sum_{j=1}^{n_c} \tau_{ij}^c + \sum_{j=1}^{n_p + 1} \tau_{ij}^p + \sum_{j=1}^{n_u} \tau_{ij}^u}{n_c + (n_p + 1) + n_u}\right] \quad (50)$$

or, equivalently

$$\pi_i^{(n_c, n_p + 1, n_u)} = \left[\frac{\tau_{i(n_p + 1)}^p + \displaystyle\sum_{j=1}^{n_c} \tau_{ij}^c + \sum_{j=1}^{n_p} \tau_{ij}^p + \sum_{j=1}^{n_u} \tau_{ij}^u}{n_c + (n_p + 1) + n_u}\right]. \quad (51)$$

This readily becomes

$$\pi_i^{(n_c, n_p + 1, n_u)} = \frac{\tau_{i(n_p + 1)}^p}{n_c + (n_p + 1) + n_u} + \left[\frac{n_c + n_p + n_u}{n_c + (n_p + 1) + n_u}\right]\pi_i^{(n_c, n_p, n_u)}, \quad (52)$$

which can be rewritten as

$$\pi_i^{(n_c, n_p + 1, n_u)} = \pi_i^{(n_c, n_p, n_u)} + \frac{1}{(n_c + n_p + n_u) + 1}\left[\tau_{i(n_p + 1)}^p - \pi_i^{(n_c, n_p, n_u)}\right]. \quad (53)$$

For uncategorized observations, it is easy to show that the correct expression is

$$\pi_i^{(n_c, n_p, n_u + 1)} = \pi_i^{(n_c, n_p, n_u)} + \frac{1}{(n_c + n_p + n_u) + 1}\left[\tau_{i(n_u + 1)}^u - \pi_i^{(n_c, n_p, n_u)}\right]. \tag{54}$$

Recursive Update Equation for μ

Consider first $\mu_i^{(n_c + 1, n_p, n_u)}$, which implies that the latest observation is class categorized. In terms of the E-M expression,

$$\mu_i^{(n_c + 1, n_p, n_u)} = \left[\frac{\displaystyle\sum_{j=1}^{n_c + 1}\left[\tau_{ij}^c x_j\right] + \sum_{j=1}^{n_p}\left[\tau_{ij}^p x_j\right] + \sum_{j=1}^{n_u}\left[\tau_{ij}^u x_j\right]}{\displaystyle\sum_{j=1}^{n_c + 1}\tau_{ij}^c + \sum_{j=1}^{n_p}\tau_{ij}^p + \sum_{j=1}^{n_u}\tau_{ij}^u}\right] \tag{55}$$

or, equivalently

$$\mu_i^{(n_c + 1, n_p, n_u)} = \left[\frac{\tau_{i(n_c + 1)}^c x_{n_c + 1} + \displaystyle\sum_{j=1}^{n_c}\left[\tau_{ij}^c x_j\right] + \sum_{j=1}^{n_p}\left[\tau_{ij}^p x_j\right] + \sum_{j=1}^{n_u}\left[\tau_{ij}^u x_j\right]}{\displaystyle\sum_{j=1}^{n_c + 1}\tau_{ij}^c + \sum_{j=1}^{n_p}\tau_{ij}^p + \sum_{j=1}^{n_u}\tau_{ij}^u}\right]. \tag{56}$$

The right-hand side of this equation can be broken into two terms, corresponding to the last observation and all previous observations, respectively.

$$\mu_i^{(n_c + 1, n_p, n_u)} = \frac{\tau_{i(n_c + 1)}^c x_{n_c + 1}}{\displaystyle\sum_{j=1}^{n_c + 1}\tau_{ij}^c + \sum_{j=1}^{n_p}\tau_{ij}^p + \sum_{j=1}^{n_u}\tau_{ij}^u} + \left[\frac{\displaystyle\sum_{j=1}^{n_c}\left[\tau_{ij}^c x_j\right] + \sum_{j=1}^{n_p}\left[\tau_{ij}^p x_j\right] + \sum_{j=1}^{n_u}\left[\tau_{ij}^u x_j\right]}{\displaystyle\sum_{j=1}^{n_c + 1}\tau_{ij}^c + \sum_{j=1}^{n_p}\tau_{ij}^p + \sum_{j=1}^{n_u}\tau_{ij}^u}\right] \tag{57}$$

This can be rewritten as

$$\mu_i^{(n_c+1,\,n_p,\,n_u)} = \frac{\tau_{i(n_c+1)}^{c} x_{n_c+1}}{\displaystyle\sum_{j=1}^{n_c+1}\tau_{ij}^{c} + \sum_{j=1}^{n_p}\tau_{ij}^{p} + \sum_{j=1}^{n_u}\tau_{ij}^{u}} + \left[\frac{\displaystyle\sum_{j=1}^{n_c}\tau_{ij}^{c} + \sum_{j=1}^{n_p}\tau_{ij}^{p} + \sum_{j=1}^{n_u}\tau_{ij}^{u}}{\displaystyle\sum_{j=1}^{n_c+1}\tau_{ij}^{c} + \sum_{j=1}^{n_p}\tau_{ij}^{p} + \sum_{j=1}^{n_u}\tau_{ij}^{u}}\right]\mu_i^{(n_c,\,n_p,\,n_u)}, \qquad (58)$$

which becomes

$$\mu_i^{(n_c+1,\,n_p,\,n_u)} = \mu_i^{(n_c,\,n_p,\,n_u)} + \frac{\tau_{i(n_c+1)}^{c}}{\displaystyle\sum_{j=1}^{n_c+1}\tau_{ij}^{c} + \sum_{j=1}^{n_p}\tau_{ij}^{p} + \sum_{j=1}^{n_u}\tau_{ij}^{u}}\left[x_{n_c+1} - \mu_i^{(n_c,\,n_p,\,n_u)}\right]. \qquad (59)$$

Consider next $\mu_{im}^{(n_c,\,n_p+1,\,n_u)}$, which implies that the latest observation is partially class categorized. In terms of the E-M expression,

$$\mu_i^{(n_c,\,n_p+1,\,n_u)} = \left[\frac{\displaystyle\sum_{j=1}^{n_c}\left[\tau_{ij}^{c}x_j\right] + \sum_{j=1}^{n_p+1}\left[\tau_{ij}^{p}x_j\right] + \sum_{j=1}^{n_u}\left[\tau_{ij}^{u}x_j\right]}{\displaystyle\sum_{j=1}^{n_c}\tau_{ij}^{c} + \sum_{j=1}^{n_p+1}\tau_{ij}^{p} + \sum_{j=1}^{n_u}\tau_{ij}^{u}}\right] \qquad (60)$$

or, equivalently

$$\mu_i^{(n_c,\,n_p+1,\,n_u)} = \left[\frac{\tau_{i(n_p+1)}^{p} + \displaystyle\sum_{j=1}^{n_c}\left[\tau_{ij}^{c}x_j\right] + \sum_{j=1}^{n_p}\left[\tau_{ij}^{p}x_j\right] + \sum_{j=1}^{n_u}\left[\tau_{ij}^{u}x_j\right]}{\displaystyle\sum_{j=1}^{n_c}\tau_{ij}^{c} + \sum_{j=1}^{n_p+1}\tau_{ij}^{p} + \sum_{j=1}^{n_u}\tau_{ij}^{u}}\right], \qquad (61)$$

this readily becomes

$$\mu_i^{(n_c, n_p + 1, n_u)} = \frac{\tau_{i(n_p+1)}^p}{\displaystyle\sum_{j=1}^{n_c} \tau_{ij}^c + \sum_{j=1}^{n_p+1} \tau_{ij}^p + \sum_{j=1}^{n_u} \tau_{ij}^u} + \left[\frac{\displaystyle\sum_{j=1}^{n_c} \tau_{ij}^c + \sum_{j=1}^{n_p} \tau_{ij}^p + \sum_{j=1}^{n_u} \tau_{ij}^u}{\displaystyle\sum_{j=1}^{n_c} \tau_{ij}^c + \sum_{j=1}^{n_p+1} \tau_{ij}^p + \sum_{j=1}^{n_u} \tau_{ij}^u}\right] \mu_i^{(n_c, n_p, n_u)} , \qquad (62)$$

which becomes

$$\mu_i^{(n_c, n_p + 1, n_u)} = \mu_i^{(n_c, n_p, n_u)} + \frac{\tau_{i(n_p+1)}^p}{\displaystyle\sum_{j=1}^{n_c} \tau_{ij}^c + \sum_{j=1}^{n_p+1} \tau_{ij}^p + \sum_{j=1}^{n_u} \tau_{ij}^u} \left[x_{i(n_p+1)} - \mu_i^{(n_c, n_p, n_u)}\right]. \qquad (63)$$

For uncategorized observations it is easy to show that the correct expression is

$$\mu_i^{(n_c, n_p, n_u + 1)} = \mu_i^{(n_c, n_p, n_u)} + \frac{\tau_{i(n_u+1)}^u}{\displaystyle\sum_{j=1}^{n_c} \tau_{ij}^c + \sum_{j=1}^{n_p} \tau_{ij}^p + \sum_{j=1}^{n_u+1} \tau_{ij}^u} \left[x_{i(n_u+1)} - \mu_i^{(n_c, n_p, n_u)}\right]. \qquad (64)$$

Recursive Update Equation for Σ

Consider first $\Sigma_i^{(n_c + 1, n_p, n_u)}$, which implies that the latest observation is class categorized. The E-M expression is

$$\Sigma_{ii}^{(n_c + 1, n_p, n_u)} = \left[\frac{\displaystyle\sum_{j=1}^{n_c+1} \left[\tau_{ij}^c (x_j - \mu_i)^2\right] + \sum_{j=1}^{n_p} \left[\tau_{ij}^p (x_j - \mu_i)^2\right] + \sum_{j=1}^{n_u} \left[\tau_{ij}^u (x_j - \mu_i)^2\right]}{\displaystyle\sum_{j=1}^{n_c+1} \tau_{ij}^c + \sum_{j=1}^{n_p} \tau_{ij}^p + \sum_{j=1}^{n_u} \tau_{ij}^u}\right] \qquad (65)$$

or, equivalently

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$$\Sigma_{ii}^{(n_c+1, n_p, n_u)} = \left[\frac{\tau_{i(n_c+1)}^c (x_{n_c+1} - \mu_i)^2}{\sum\limits_{j=1}^{n_c+1} \tau_{ij}^c + \sum\limits_{j=1}^{n_p} \tau_{ij}^p + \sum\limits_{j=1}^{n_u} \tau_{ij}^u} \right]$$

$$+ \left[\frac{\sum\limits_{j=1}^{n_c} \left[\tau_{ij}^c (x_j - \mu_i)^2 \right] + \sum\limits_{j=1}^{n_p} \left[\tau_{ij}^p (x_j - \mu_i)^2 \right] + \sum\limits_{j=1}^{n_u} \left[\tau_{ij}^u (x_j - \mu_i)^2 \right]}{\sum\limits_{j=1}^{n_c+1} \tau_{ij}^c + \sum\limits_{j=1}^{n_p} \tau_{ij}^p + \sum\limits_{j=1}^{n_u} \tau_{ij}^u} \right]. \tag{66}$$

This can be rewritten as

$$\Sigma_{ii}^{(n_c+1, n_p, n_u)} = \frac{\tau_{i(n_c+1)}^c (x_{n_c+1} - \mu_i)^2}{\sum\limits_{j=1}^{n_c+1} \tau_{ij}^c + \sum\limits_{j=1}^{n_p} \tau_{ij}^p + \sum\limits_{j=1}^{n_u} \tau_{ij}^u} + \left[\frac{\sum\limits_{j=1}^{n_c} \tau_{ij}^c + \sum\limits_{j=1}^{n_p} \tau_{ij}^p + \sum\limits_{j=1}^{n_u} \tau_{ij}^u}{\sum\limits_{j=1}^{n_c+1} \tau_{ij}^c + \sum\limits_{j=1}^{n_p} \tau_{ij}^p + \sum\limits_{j=1}^{n_u} \tau_{ij}^u} \right] \Sigma_{ii}^{(n_c, n_p, n_u)}, \tag{67}$$

which becomes

$$\Sigma_{ii}^{(n_c+1, n_p, n_u)} = \Sigma_{ii}^{(n_c, n_p, n_u)} + \frac{\tau_{i(n_c+1)}^c}{\sum\limits_{j=1}^{n_c+1} \tau_{ij}^c + \sum\limits_{j=1}^{n_p} \tau_{ij}^p + \sum\limits_{j=1}^{n_u} \tau_{ij}^u} \left[(x_{n_c+1} - \mu_i)^2 - \Sigma_{ii}^{(n_c, n_p, n_u)} \right]. \tag{68}$$

Similarly, for partially categorized and uncategorized data, respectively,

$$\Sigma_{ii}^{(n_c, n_p+1, n_u)} = \Sigma_{ii}^{(n_c, n_p, n_u)} + \frac{\tau_{i(n_p+1)}^p}{\sum\limits_{j=1}^{n_c+1} \tau_{ij}^c + \sum\limits_{j=1}^{n_p+1} \tau_{ij}^p + \sum\limits_{j=1}^{n_u} \tau_{ij}^u} \left[(x_{n_p+1} - \mu_i)^2 - \Sigma_{ii}^{(n_c, n_p, n_u)} \right] \tag{69}$$

and

$$\Sigma_{ii}^{(n_c, n_p, n_u + 1)} = \Sigma_{ii}^{(n_c, n_p, n_u)} + \frac{\tau_{i\,(n_u + 1)}^{u}}{\displaystyle\sum_{j=1}^{n_c} \tau_{ij}^{c} + \sum_{j=1}^{n_p} \tau_{ij}^{p} + \sum_{j=1}^{n_u + 1} \tau_{ij}^{u}} \left[(x_{n_u + 1} - \mu_i)^2 - \Sigma_{ii}^{(n_c, n_p, n_u)} \right]. \quad (70)$$

RESULTS

SUMMARY OF UNIVARIATE ITERATIVE E-M UPDATE EQUATIONS

For completeness, the iterative E-M equations are reproduced first.

$$\zeta_{im} = \left[\frac{1}{\displaystyle\sum_{j=1}^{n_c} \sum_{m=1}^{M} \tau_{ijm} + \sum_{j=1}^{n_p} \tau_{ij}^{p}} \right] \left[\sum_{j=1}^{n_c} \tau_{ijm} + \sum_{j=1}^{n_p} \xi_{jm} \tau_{ij}^{p} \right], \quad (71)$$

$$\pi_i = \frac{1}{(n_c + n_p + n_u)} \left[\sum_{j=1}^{n_c} \tau_{ij}^{c} + \sum_{j=1}^{n_p} \tau_{ij}^{p} + \sum_{j=1}^{n_u} \tau_{ij}^{u} \right], \quad (72)$$

$$\mu_i = \frac{\displaystyle\sum_{j=1}^{n_c} \left[\tau_{ij}^{c} x_j \right] + \sum_{j=1}^{n_p} \left[\tau_{ij}^{p} x_j \right] + \sum_{j=1}^{n_u} \left[\tau_{ij}^{u} x_j \right]}{\left[\displaystyle\sum_{j=1}^{n_c} \left[\tau_{ij}^{c} \right] + \sum_{j=1}^{n_p} \left[\tau_{ij}^{p} \right] + \sum_{j=1}^{n_u} \left[\tau_{ij}^{u} \right] \right]}, \quad (73)$$

$$\Sigma_{ii} = \frac{\displaystyle\sum_{j=1}^{n_c} \tau_{ij}^{c} (x_j - \mu_i)^2 + \sum_{j=1}^{n_p} \tau_{ij}^{p} (x_j - \mu_i)^2 + \sum_{j=1}^{n_u} \tau_{ij}^{u} (x_j - \mu_i)^2}{\left[\displaystyle\sum_{j=1}^{n_c} \tau_{ij}^{c} + \sum_{j=1}^{n_p} \tau_{ij}^{p} + \sum_{j=1}^{n_u} \tau_{ij}^{u} \right]}, \quad (74)$$

where

$$\tau_{ijm} = \frac{z_{jm}\zeta_{im}\pi_i f(x_j;\theta_i)}{\displaystyle\sum_{i=1}^{g}\sum_{m=1}^{M} z_{jm}\zeta_{im}\pi_i f(x_j;\theta_i)} \tag{75}$$

and

$$\tau_{ij}^c = \sum_{m=1}^{M}\tau_{ijm} = \frac{\zeta_{im_j}\pi_i f(x_j;\theta_i)}{\displaystyle\sum_{i=1}^{g}\zeta_{im_j}\pi_i f(x_j;\theta_i)} = \frac{\displaystyle\sum_{m=1}^{M} z_{jm}\zeta_{im}\pi_i f(x_j;\theta_i)}{\displaystyle\sum_{i=1}^{g}\sum_{m=1}^{M} z_{jm}\zeta_{im}\pi_i f(x_j;\theta_i)}. \tag{76}$$

Similarly

$$\tau_{ij}^p = \tau_{ij}^u = \frac{\pi_i f(x_j;\theta_i)}{\displaystyle\sum_{i=1}^{g}\pi_i f(x_j;\theta_i)}, \tag{77}$$

where it is to be remembered that τ_{ij}^p is only computed when x_j is a partially categorized observation and similarly for τ_{ij}^u.

The E-M algorithm then consists of iterating the expectation step consisting of evaluating Equations (75), (76), and (77) for the appropriate observations and the maximization step, which consists of evaluating new parameter values using Equations (71) through (74).

The multivariate versions can be obtained by making x_j and μ_i vector quantities and Σ_i a matrix. The equations for μ_i and Σ_i become

$$\mu_i^k = \frac{\displaystyle\sum_{i=1}^{n_c}\left[\tau_{ij}^c x_j^k\right] + \sum_{j=1}^{n_p}\left[\tau_{ij}^p x_j^k\right] + \sum_{j=1}^{n_u}\left[\tau_{ij}^u x_j^k\right]}{\left[\displaystyle\sum_{j=1}^{n_c}\left[\tau_{ij}^c\right] + \sum_{j=1}^{n_p}\left[\tau_{ij}^p\right] + \sum_{j=1}^{n_u}\left[\tau_{ij}^u\right]\right]} \tag{78}$$

and

$$\Sigma_i^{kl} = \frac{\sum_{j=1}^{n_c} \tau_{ij}^c \left(x_j^k - \mu_i^k \right)\left(x_j^l - \mu_i^l \right) + \sum_{j=1}^{n_p} \tau_{ij}^p \left(x_j^k - \mu_i^k \right)\left(x_j^l - \mu_i^l \right) + \sum_{j=1}^{n_u} \tau_{ij}^u \left(x_j^k - \mu_i^k \right)\left(x_j^l - \mu_i^l \right)}{\left[\sum_{j=1}^{n_c} \tau_{ij}^c + \sum_{j=1}^{n_p} \tau_{ij}^p + \sum_{j=1}^{n_u} \tau_{ij}^u \right]}, \quad (79)$$

where the component indices are denoted by superscripts.

SUMMARY OF UNIVARIATE RECURSIVE UPDATE EQUATIONS

Categorized Observation

$$\zeta_{im}^{(n_c+1, n_p)} = \zeta_{im}^{(n_c, n_p)} + \frac{\tau_{i(n_c+1)}^c \cdot \left[z_{(n_c+1)m} - \zeta_{im}^{(n_c, n_p)} \right]}{\tau_{i(n_c+1)}^c + \sum_{j=1}^{n_c} \tau_{ij}^c + \sum_{j=1}^{n_p} \tau_{ij}^p}. \quad (80)$$

$$\pi_i^{(n_c+1, n_p, n_u)} = \pi_i^{(n_c, n_p, n_u)} + \frac{1}{(n_c + n_p + n_u) + 1} \left[\tau_{i(n_c+1)}^c - \pi_i^{(n_c, n_p, n_u)} \right]. \quad (81)$$

$$\mu_i^{(n_c+1, n_p, n_u)} = \mu_i^{(n_c, n_p, n_u)} + \frac{\tau_{i(n_c+1)}^c}{\sum_{j=1}^{n_c+1} \tau_{ij}^c + \sum_{j=1}^{n_p} \tau_{ij}^p + \sum_{j=1}^{n_u} \tau_{ij}^u} \left[x_{n_c+1} - \mu_i^{(n_c, n_p, n_u)} \right]. \quad (82)$$

$$\Sigma_{ii}^{(n_c+1, n_p, n_u)} = \Sigma_{ii}^{(n_c, n_p, n_u)} + \frac{\tau_{i(n_c+1)}^c}{\sum_{j=1}^{n_c+1} \tau_{ij}^c + \sum_{j=1}^{n_p} \tau_{ij}^p + \sum_{j=1}^{n_u} \tau_{ij}^u} \left[(x_{n_c+1} - \mu_i)^2 - \Sigma_{ii}^{(n_c, n_p, n_u)} \right]. \quad (83)$$

For the multivariate case, Equations (82) and (83) become (with vector indices k and l)

$$\mu_i^{k(n_c+1,\,n_p,\,n_u)} = \mu_i^{k(n_c,\,n_p,\,n_u)} + \frac{\tau_{i(n_c+1)}^c}{\sum\limits_{j=1}^{n_c+1}\tau_{ij}^c + \sum\limits_{j=1}^{n_p}\tau_{ij}^p + \sum\limits_{j=1}^{n_u}\tau_{ij}^u}\left[x_{n_c+1}^k - \mu_i^{k(n_c,\,n_p,\,n_u)}\right], \qquad (84)$$

$$\Sigma_i^{kl(n_c+1,\,n_p,\,n_u)} = \Sigma_i^{kl(n_c,\,n_p,\,n_u)}$$
$$+ \frac{\tau_{i(n_c+1)}^c}{\sum\limits_{j=1}^{n_c+1}\tau_{ij}^c + \sum\limits_{j=1}^{n_p}\tau_{ij}^p + \sum\limits_{j=1}^{n_u}\tau_{ij}^u}\left[\left(x_{n_c+1}^k - \mu_i^k\right)\left(x_{n_c+1}^l - \mu_i^l\right) - \Sigma_i^{kl(n_c,\,n_p,\,n_u)}\right]. \qquad (85)$$

Partially Categorized Observation

$$\zeta_{im}^{(n_c,\,n_p+1)} = \zeta_{im}^{(n_c,\,n_p)} + \left[\frac{\tau_{i,\,n_p+1}^p}{\tau_{i,\,n_p+1}^p + \sum\limits_{j=1}^{n_c}\tau_{ij}^c + \sum\limits_{j=1}^{n_p}\tau_{ij}^p}\right]\left[\xi_{jm} - \zeta_{im}^{(n_c,\,n_p)}\right]. \qquad (86)$$

$$\pi_i^{(n_c,\,n_p+1,\,n_u)} = \pi_i^{(n_c,\,n_p,\,n_u)} + \frac{1}{(n_c+n_p+n_u)+1}\left[\tau_{i(n_p+1)}^p - \pi_i^{(n_c,\,n_p,\,n_u)}\right]. \qquad (87)$$

$$\mu_i^{(n_c,\,n_p+1,\,n_u)} = \mu_i^{(n_c,\,n_p,\,n_u)} + \frac{\tau_{i(n_p+1)}^p}{\sum\limits_{j=1}^{n_c}\tau_{ij}^c + \sum\limits_{j=1}^{n_p+1}\tau_{ij}^p + \sum\limits_{j=1}^{n_u}\tau_{ij}^u}\left[x_{n_p+1} - \mu_i^{(n_c,\,n_p,\,n_u)}\right]. \qquad (88)$$

$$\Sigma_{ii}^{(n_c,\,n_p+1,\,n_u)} = \Sigma_{ii}^{(n_c,\,n_p,\,n_u)} + \frac{\tau_{i(n_p+1)}^p}{\sum\limits_{j=1}^{n_c}\tau_{ij}^c + \sum\limits_{j=1}^{n_p+1}\tau_{ij}^p + \sum\limits_{j=1}^{n_u}\tau_{ij}^u}\left[\left(x_{n_p+1} - \mu_i\right)^2 - \Sigma_{ii}^{(n_c,\,n_p,\,n_u)}\right]. \qquad (89)$$

For the multivariate case, Equations (88) and (89) become (with vector indices k and l)

$$\mu_i^{k\,(n_c,\,n_p+1,\,n_u)} = \mu_i^{k\,(n_c,\,n_p,\,n_u)} + \frac{\tau_{i\,(n_p+1)}^{p}}{\displaystyle\sum_{j=1}^{n_c}\tau_{ij}^{c} + \sum_{j=1}^{n_p+1}\tau_{ij}^{p} + \sum_{j=1}^{n_u}\tau_{ij}^{u}}\left[x_{n_p+1}^{k} - \mu_i^{k\,(n_c,\,n_p,\,n_u)}\right], \qquad (90)$$

$$\Sigma_i^{kl\,(n_c,\,n_p+1,\,n_u)} = \Sigma_i^{kl\,(n_c,\,n_p,\,n_u)}$$

$$+ \frac{\tau_{i\,(n_p+1)}^{p}}{\displaystyle\sum_{j=1}^{n_c}\tau_{ij}^{c} + \sum_{j=1}^{n_p+1}\tau_{ij}^{p} + \sum_{j=1}^{n_u}\tau_{ij}^{u}}\left[\left(x_{n_p+1}^{k} - \mu_i^{k}\right)\left(x_{n_p+1}^{l} - \mu_i^{l}\right) - \Sigma_i^{kl\,(n_c,\,n_p,\,n_u)}\right]. \qquad (91)$$

Uncategorized Observation

$$\pi_i^{(n_c,\,n_p,\,n_u+1)} = \pi_i^{(n_c,\,n_p,\,n_u)} + \frac{1}{(n_c+n_p+n_u)+1}\left[\tau_{i\,(n_u+1)}^{u} - \pi_i^{(n_c,\,n_p,\,n_u)}\right]. \qquad (92)$$

$$\mu_i^{(n_c,\,n_p,\,n_u+1)} = \mu_i^{(n_c,\,n_p,\,n_u)} + \frac{\tau_{i\,(n_u+1)}^{u}}{\displaystyle\sum_{j=1}^{n_c}\tau_{ij}^{c} + \sum_{j=1}^{n_p}\tau_{ij}^{p} + \sum_{j=1}^{n_u+1}\tau_{ij}^{u}}\left[x_{n_u+1} - \mu_i^{(n_c,\,n_p,\,n_u)}\right]. \qquad (93)$$

$$\Sigma_{ii}^{(n_c,\,n_p,\,n_u+1)} = \Sigma_{ii}^{(n_c,\,n_p,\,n_u)} + \frac{\tau_{i\,(n_u+1)}^{u}}{\displaystyle\sum_{j=1}^{n_c}\tau_{ij}^{c} + \sum_{j=1}^{n_p}\tau_{ij}^{p} + \sum_{j=1}^{n_u+1}\tau_{ij}^{u}}\left[(x_{n_u+1} - \mu_i)^2 - \Sigma_{ii}^{(n_c,\,n_p,\,n_u)}\right]. \qquad (94)$$

For the multivariate case, Equations (88) and (89) become (with vector indices k and l)

$$\mu_i^{k\,(n_c,\,n_p,\,n_u+1)} = \mu_i^{k\,(n_c,\,n_p,\,n_u)} + \frac{\tau_{i\,(n_u+1)}^{u}}{\displaystyle\sum_{j=1}^{n_c}\tau_{ij}^{c} + \sum_{j=1}^{n_p}\tau_{ij}^{p} + \sum_{j=1}^{n_u+1}\tau_{ij}^{u}}\left[x_{n_u+1}^{k} - \mu_i^{k\,(n_c,\,n_p,\,n_u)}\right], \qquad (95)$$

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$$\Sigma_i^{kl\,(n_c,\,n_p,\,n_u+1)} = \Sigma_i^{kl\,(n_c,\,n_p,\,n_u)}$$

$$+ \frac{\tau_{i\,(n_u+1)}^{u}}{\displaystyle\sum_{j=1}^{n_c} \tau_{ij}^{c} + \sum_{j=1}^{n_p} \tau_{ij}^{p} + \sum_{j=1}^{n_u+1} \tau_{ij}^{u}} \left[\left(x_{n_u+1}^{k} - \mu_i^{k} \right) \left(x_{n_u+1}^{l} - \mu_i^{l} \right) - \Sigma_i^{kl\,(n_c,\,n_p,\,n_u)} \right]. \qquad (96)$$

CONCLUSIONS

The derivation of the recursive E-M equations for joint representation mixture models with normal components has been presented. While the detailed derivation was for the univariate case, a slightly more complicated derivation results in the full multivariate equations. The results for this case have been presented without derivation.

The joint representation approach represents a significant philosophical departure from current mixture model usage. The standard mixture model usage is either to build a separate mixture model for each class when the observations are class labeled, or to assume that each class is normally distributed so that a mixture model for all the data can be interpreted as a mixture of normal classes. This approach, in effect, totally relaxes the requirement for each class to be normally distributed. Philosophically, a semiparametric viewpoint has been taken in that it is assumed that each class can be modelled by a (potentially complex) mixture model and that no significance is to be ascribed to an individual term in the mixture. As an example, contrast a mixture model approximation to a lognormal density to a mixture of two normals. In the latter case, it may well make sense to care about which of the two terms gave rise to a particular observation. However, in the lognormal case, where by assumption the density is nonparametric with respect to representation by normal mixtures, this sort of distinction has little or no meaning.

This approach is thus appropriate for combined supervised/unsupervised (various levels of class categorization) learning when the individual class densities may be more complex than simple normals. It provides a unified framework for handling this problem. Once the joint representation density has been estimated, densities corresponding to the individual classes can be easily recovered.

The recursive versions of these equations allow this approach to be used for large data sets as well as in an adaptive mixture model framework.

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